20 Years of the Atlantic Meridional Transect — AMT

Andrew Rees, Carol Robinson, Tim Smyth, Jim Aiken, Phil Nightingale, and Mike Zubkov

Introduction

The AMT (www.amt-uk.org) is a multidisciplinary programme which undertakes biological, chemical, and physical oceanographic research during an annual voyage between the UK and a destination in the South Atlantic such as the Falkland Islands, South Africa, or Chile. This transect of >12,000 km crosses a range of ecosystems from subpolar to tropical, from euphotic shelf seas and upwelling systems, to oligotrophic mid-ocean gyres.

The year 2015 has seen two milestones in the history of the AMT: the achievement of 20 years of this unique ocean going programme and the departure of the 25th cruise on the 15th of September. Both of these events were celebrated in June this year with an open science conference hosted by the Plymouth Marine Laboratory (PML) and will be further documented in a special issue of Progress in Oceanography which is planned for publication in 2016. Since 1995, the 25 research cruises have involved 242 sea-going scientists from 66 institutes representing 22 countries.

AMT was designed from the outset to be a collaborative programme. It was originally conceived by Jim Aiken, Patrick Holligan, Roger Harris, and Dave Robins with Chuck McClain and Chuck Trees at NASA to test and ground truth satellite algorithms of ocean color. The opportunities offered by this initiative meant that this series of repeated biannual cruises rapidly developed into a coordinated study of ocean biodiversity, biogeochemistry, and ocean/atmosphere interactions.

Phase One

The first cruises used the passage of the Royal Research Ship (RRS) *James Clark Ross* as a ship of opportunity between the UK and the Falkland Islands (~50°N – 52°S) southwards in September and northwards in April each year (Fig. 1). The scientific aims included (1) an assessment of mesoscale to basin scale variability in phytoplankton processes, (2) the functional interpretation of bio-optical signatures, and (3) the seasonal, regional, and latitudinal variations in mesozooplankton dynamics (Aiken et al. 2000). Funding during the first 5-year period was provided by the UK Natural Environment Research Council (NERC) through two Plankton Reactivity in the Marine Environment (PRIME) research grants and the PML Core Strategic Research Programme, with additional funds from NASA (USA), CANIGO (EU), and the Ministry of Science and Technology (Spain).

Phase Two

In 2002, AMT aims were broadened to address a suite of cross disciplinary questions concerning ocean plankton ecology and biogeochemistry and their links to atmospheric processes. A primary aim was to provide data for use in the development of models to describe the interactions between the global climate system, plankton functional biodiversity, and ocean/atmosphere biogeochemistry. The specific objectives were to determine (1) how the structure, functional properties, and trophic status of the major planktonic ecosystems vary in space and time; (2) how physical processes control the rates of nutrient supply, including dissolved organic matter, to the planktonic ecosystem; and (3) how atmosphere–ocean exchange and photo-degradation influence the formation and fate of organic matter. The AMT also continued to provide a platform for national and international scientific collaboration, for training the next generation of oceanographers and for developing and validating novel technologies. The programme received support through an award to Carol Robinson at PML of the first NERC Consortium Grant (2002–2006).

Phase Three

The formal aims of the third phase of the AMT (2007–2012), in addition to continuing to serve as an open ocean in situ observing system, were to: (1) give warning of any fundamental change in Atlantic ecosystem functioning; (2) improve forecasts of the ocean's future state and associated socioeconomic

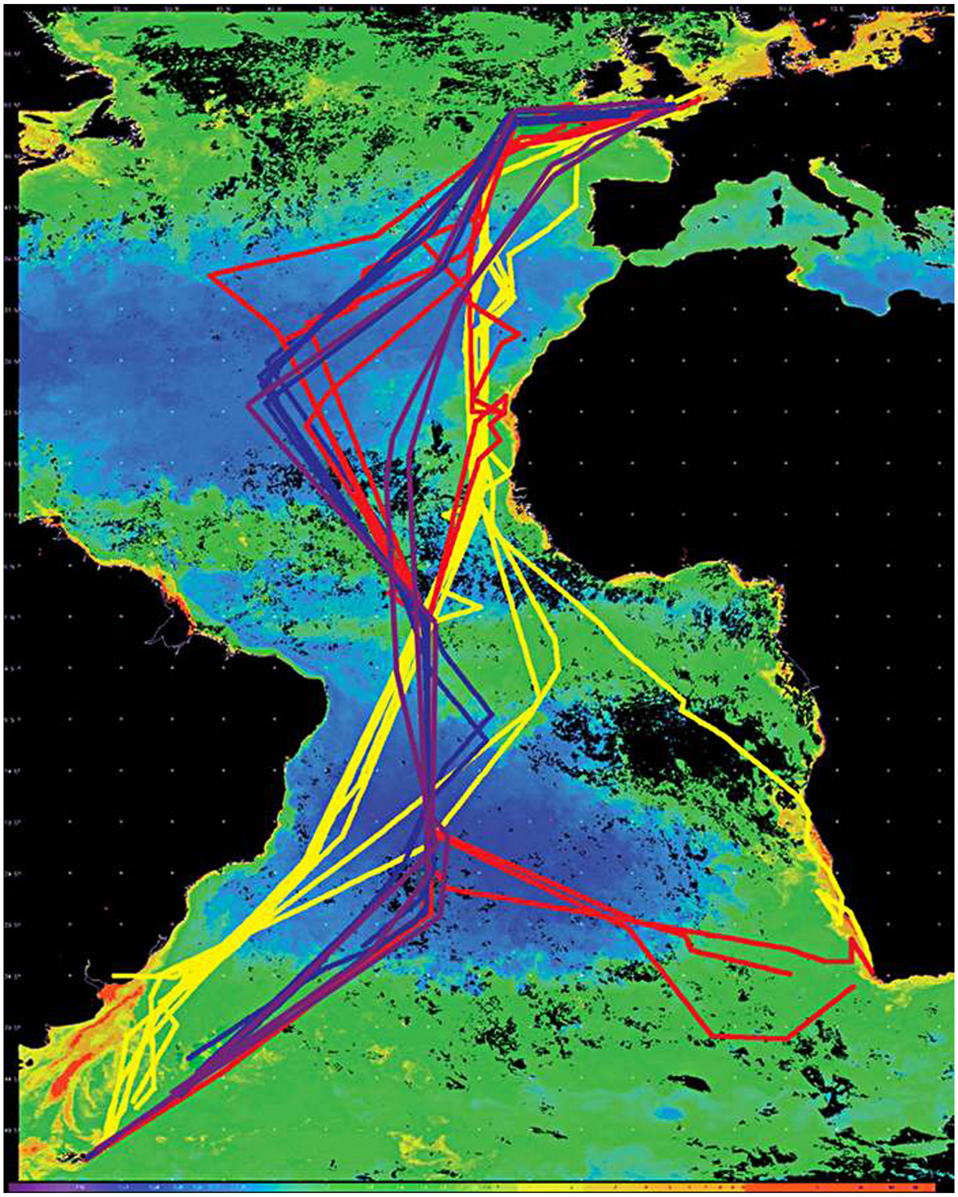

Fig. 1. Composite chlorophyll a image (courtesy of NEODAAS) of the Atlantic Ocean for the month of October 2009 (AMT19) overlain with cruise tracks AMT1 to AMT25. AMT1 to 11, 1995 – 2000, phase 1 yellow; AMT12 to 17, 2002 – 2006, phase 2 – red; AMT18 to 22, 2007 – 2012, phase 3 – blue; AMT23 to 25, 2012 to 2015, phase 4 – purple.

impacts and; (3) provide a 'contextual' logistical and scientific infrastructure for independently funded biogeochemists and ecologists that join the AMT cruises. The training of the next generation of oceanographers was further enhanced through a new collaboration with the Scientific Committee on Oceanic Research (SCOR) and the Partnership for Observation of the Global Oceans (POGO; www.ocean-partners.org) to enable cruise participation and scientific collaboration for young researchers from developing countries. The third phase of AMT (2007–2012) was funded via the NERC Marine Centres' strategic research programme 'Oceans 2025' (www.oceans2025.org) through awards made to PML and the National Oceanography Centre (NOC).

Phase Four

In 2008, cruise time was reduced from biannual to annual, taking place during the boreal autumn—austral spring. Throughout the lifetime of the AMT the specific objectives have evolved to enable the collection of a continuous set of observations whilst addressing current concerns and remaining relevant to global issues that are raised throughout the most recent IPCC assessment and UK environmental strategy. For this phase of the programme the objectives are to: (1) quantify the nature and causes of ecological and biogeochemical variability in planktonic ecosystems; (2) quantify the effects of this variability on nutrient cycling, on biogenic export and on air–sea exchange of climate active gases; (3) construct a multidecadal, multidisciplinary ocean time-series which is integrated within a wider "Pole-to-pole" observatory concept; (4) deliver essential sea-truth validation for current and next generation satellite missions; (5) generate and make available, essential data for global ecosystem model development and validation and; (6) provide a valuable, highly sought after training arena for the next generation of UK and International oceanographers. AMT objectives also align with those of the SCOR/IGBP (Integrated Geosphere-Biosphere Programme; www.igbp.net) sponsored international programmes IMBER (Integrated Marine Biogeochemistry and Ecosystem Research; www.imber.info), SOLAS (Surface Ocean Lower Atmosphere Study; www.solas-int.org), and GEOTRACES (Study of the marine biogeochemical cycles of trace elements and their isotopes; www.geotraces.org). Oceans 2025 funding was superseded by a NERC National Capability (NC) award which has enabled the continuation of AMT into the foreseeable future.

AMT is unique in its ability to acquire data on long north–south transects of the Atlantic Ocean and to make observations on basin scales. It represents the longest running programme based in the Atlantic Ocean that makes repeat measurements of core parameters and provides a platform for multidisciplinary oceanographic research. This spatially extensive decadal dataset is made available to the wider community through the British Oceanographic Data Centre (http://www.bodc.ac.uk/projects/uk/amt/). Datasets include:

- Vertical CTD profiles and continuous underway data
- Optical characteristics of the water column

- Biogeochemical measurements including nutrients, pigments, dissolved gases, and particulate carbon and nitrogen
- Primary, net and new production, and respiration measurements

Of the core measurements that have been identified as Essential Ocean Variables (EOVs) by the International Ocean Carbon Coordination Project (IOCCP) as part of the GOOS Integrated Framework for Sustained Ocean Observing (FOO—http://www.ioccp.org/index.php/foo), seven of the nine are measured routinely during AMT cruises, namely: oxygen, macronutrients, carbonate system, suspended particulate matter, nitrous oxide, and dissolved organic matter.

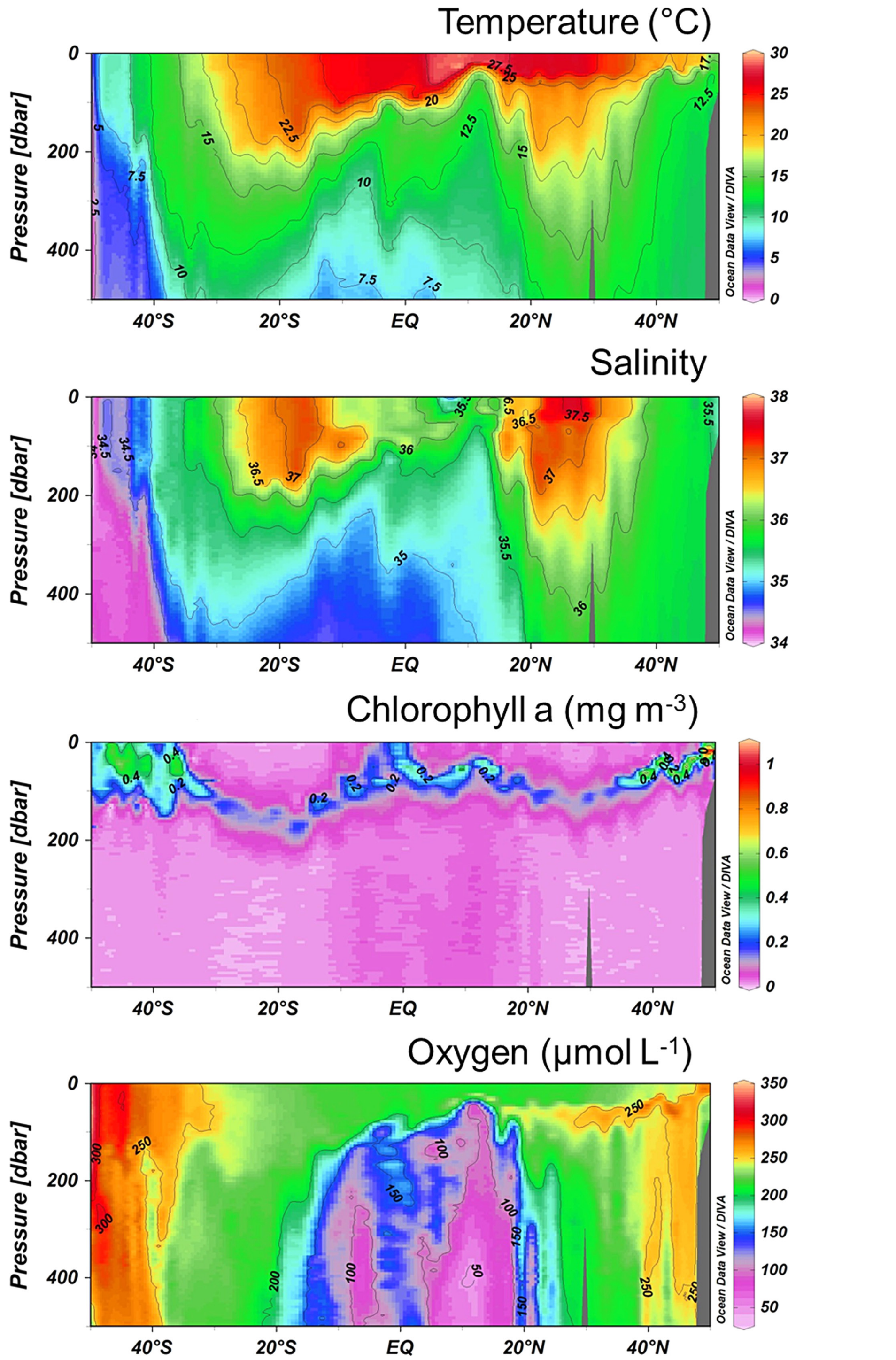

Fig. 2. Exemplar profiles of environmental variables collected during AMT24 (September – October 2014). *Image produced using Ocean Data View* (http://odv.awi.de/).

AMT Contributions to Contemporary Oceanography

To date AMT scientists have published 243 peer reviewed papers (http://www.amt-uk.org/Publications) which include a special issue of Progress in Oceanography (Aiken et al. 2000) and two issues of Deep-Sea Research II (Robinson et al. 2006, 2009). The IMBER programme in its Science Plans (IGBP Reports 52 and 52A) recognised the importance of understanding the relationship between genetic, morphological, physiological, and behavioral characteristics of marine organisms together with their biogeochemical functioning to determine cycles of macronutrients and micronutrients and the production, remineralization, transport, and transformation of organic matter. AMT achievements which have contributed to this IMBER theme include the first Atlantic Ocean basin scale measurements of *Prochlorococcus* and *Synechococcus* abundance (Zubkov et al. 2000), the biodiversity of which also informed on the extent of distinct biogeographical provinces within the Atlantic Ocean. Other "firsts" for the AMT which relate to the IMBER goals include the first description over ocean basin scales of plankton net community production (Serret et al. 2001), nitrification (Clark et al. 2007), mixotrophy (Hartman et al. 2012), and photoheterotrophy (Evans et al. 2015).

AMT research has contributed to the goals of SOLAS (IGBP Report 50 and Future Earth report in review), which is to achieve quantitative understanding of the key biogeochemical–physical interactions and feedbacks between the ocean and the atmosphere.

Isotopic measurements of aerosol ammonium provided evidence for the existence of a marine ammonia source and offers a method to define the relative contribution of marine and terrestrial ammonium to aerosols in remote areas and thereby investigate the role of these emissions in climate regulation (Jickells et al. 2003). The extensive AMT dataset of dimethylsulphide (DMS) and dimethylsulphoniopropionate (DMSP) showed strong correlations with primary production and some photo-protective pigments, a first

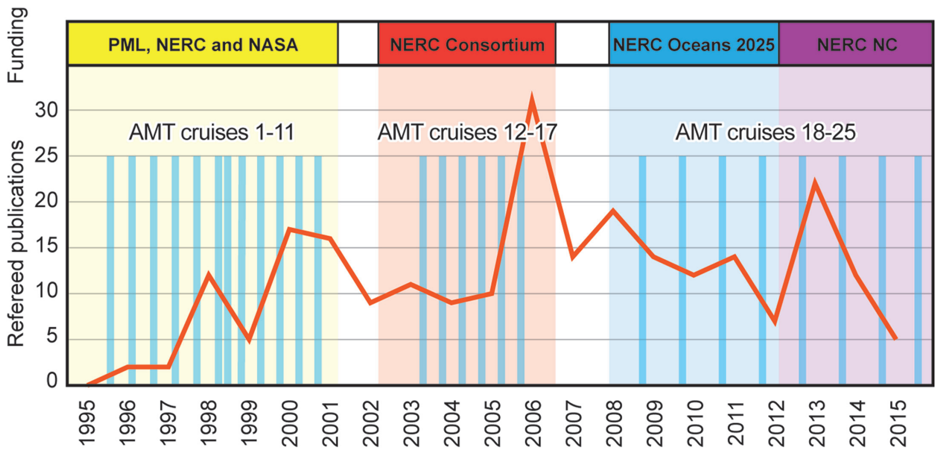

Fig. 3. Timeline of AMT cruises (blue bars), publications (red line) and funding regimes between 1995 and 2015.

step for global prediction and model-validation of these climate relevant compounds (Bell et al. 2006). Measurements made on AMT 12 and 13 suggest that the Atlantic Ocean accounts for 6–15% and 4–13% of the global marine sources of atmospheric N_2O and CH_4, respectively (Forster et al. 2009). Methanol is the second most abundant organic gas in the troposphere and in the surface ocean represents a supply of energy and carbon for marine microbes. Yang et al. (2013) determined the air to sea flux of methanol using the eddy covariance method and showed a consistent influx of methanol from the atmosphere throughout the 10,000 km transect. This study also helped to constrain the molecular diffusional resistance above the ocean surface, an important term for improving air–sea gas exchange models.

The GEOTRACES science plan (http://www.geotraces.org/libraries/documents/Science_plan.pdf) recognises a guiding mission to: identify processes and quantify fluxes that control the distributions of key trace elements and isotopes in the ocean, and to establish the sensitivity of these distributions to changing environmental conditions. AMT scientists have played a part in the development of methodology that has enabled this research, in addition to determining concentrations, fluxes and the uptake of trace metals that are of relevance to the GEOTRACES programme. Richier et al. (2012) combined laboratory and AMT field-based quantifications of the absolute concentrations of key enzymes involved in both photosynthesis and nitrogen fixation to determine how *Trichodesmium* allocates resources to these processes. They found that their estimates of cellular metabolic iron requirements are consistent with the availability of this trace metal playing a major role in restricting the biomass and activity of *Trichodesmium* throughout much of the subtropical Atlantic Ocean. The input of mineral dust from the atmosphere can supply iron and other trace metals to the remote ocean and can influence the marine carbon cycle due to iron's role as a potentially limiting micronutrient. Baker et al. (2013) used aerosol and rainwater samples collected during AMT cruises to estimate the atmospheric input of iron, aluminium, and manganese to regions of the Atlantic Ocean. As was found for C and N, inputs were highest in regions of high precipitation (the intertropical convergence zone and South Atlantic storm track), and rainfall contributed higher proportions of total input to wetter regions. Dissolved (dFe) and atmospheric fluxes of iron revealed a strong disparity between the iron biogeochemistry of the North and South Atlantic Ocean with the highest dFe and lowest mixed layer residence times found in the northern tropical and subtropical regions (Ussher et al. 2013) which confirmed in part the findings of Moore et al. (2009) that inter-basin differences in nitrogen fixation are controlled by iron supply rather than phosphorus availability.

Current AMT Subjects and Goals

1) The nature and causes of ecological and biogeochemical variability in planktonic ecosystems

The uniqueness of AMT is that it regularly traverses the remote and hence understudied two subtropical gyres of the oligotrophic Atlantic ocean. The oligotrophic ocean is the most extensive biome on Earth where SAR11 and *Prochlorococcus* bacterioplankton numerically dominate the surface waters depleted in inorganic macronutrients as well as in dissolved organic matter. In such nutrient poor conditions both SAR11 and *Prochlorococcus* become photoheterotrophic, that is, they enhance uptake of scarce organic molecules using plentiful solar radiation to energise appropriate transport systems to develop an alternative type of photosynthesis (Gómez-Pereira et al. 2013). The AMT programme continues to reveal unprecedented biogeochemical phenomena. *Prochlorococcus* are the most abundant photosynthetic organisms on the planet, however, in the oligotrophic open ocean, the majority of their cells in the top half of the photic layer have levels of photosynthetic pigmentation barely detectable by flow cytometry, suggesting low efficiency of CO_2 fixation compared with other phytoplankton living in the same waters. Hartmann et al. (2014) have shown that this is not the case and their data indicate that in oligotrophic oceanic surface waters, pigment minimization allows *Prochlorococcus* cells to harvest plentiful sunlight more effectively than other phytoplankton. Zubkov (2014) tested his hypothesis that if eukaryotes can use their superior energetic resources to acquire nutrients with more or even similar efficiency compared with prokaryotes, larger unicellular eukaryotes should be able to achieve higher growth rates than smaller cyanobacteria. His observations from several AMT cruises showed that at the ocean basin scale, cyanobacteria double their biomass twice as frequently as the picoeukaryotes indicating that the prokaryotes are faster growing CO_2 fixers, better adapted to phototrophic living in the oligotrophic open ocean.

2) The effects of ecological and biogeochemical variability on nutrient cycling, biogenic export and on air–sea exchange of climate active gases

The extended range of the AMT through contrasting ocean provinces has allowed the development of new methods and techniques for measuring key trace substances in both the atmosphere and ocean. A particular focus has been on the concentration of Oxygenated Volatile Organic Compounds (OVOCs) such as methanol, acetaldehyde, and acetone. These substances are present in very low concentrations, and their uptake mechanisms and cycling within the ocean and atmosphere is now being elucidated by measurements taken on AMT cruises. Concentrations of methanol and acetone varied over the track with enrichment in the oligotrophic Northern Atlantic Gyre, whereas acetaldehyde showed less variability over the full extent of the transect. OVOC concentrations did not consistently correlate with primary production or chlorophyll *a* levels, although a significant relationship was found indicating that acetone might be removed by marine bacteria as a source of carbon (Beale et al. 2013). The role of these OVOCs in marine waters is still not fully understood. Dixon et al. (2013) reported the first microbial methanol carbon assimilation rates to find that on average, rates in coastal upwelling waters were 11 times greater than open ocean northern temperate and eight times greater than in the oligotrophic gyres. Microbes in the coastal upwelling used up to 57% of the total methanol for assimilation of the carbon into cells, compared with an average of 1% in gyre waters.

During AMT20 a laser-based analyser for nitrous oxide, carbon monoxide, and water vapor was coupled to an equilibrator for continuous high-resolution dissolved gas measurements in the surface ocean along the north to south transect. A comparison between the field and laboratory measurements showed high precision and accuracy for nitrous oxide. The subtropical gyres were slightly undersaturated whereas the equatorial region was a source of nitrous oxide to the atmosphere. The ability to measure at high temporal and spatial resolution revealed submesoscale variability in dissolved N_2O concentrations. The magnitude of the observed saturation is in agreement with published data. Mean sea-to-air fluxes in the tropical and subtropical Atlantic ranged between -1.6 and $0.11\ \mu mol\ m^{-2}\ d^{-1}$ and confirmed that the subtropical Atlantic is not an important source region for N_2O to the atmosphere, compared to average global fluxes of $0.6\ \mu mol\ m^{-2}\ d^{-1}$ to $2.4\ \mu mol\ m^{-2}\ d^{-1}$ (Grefe and Kaiser 2014).

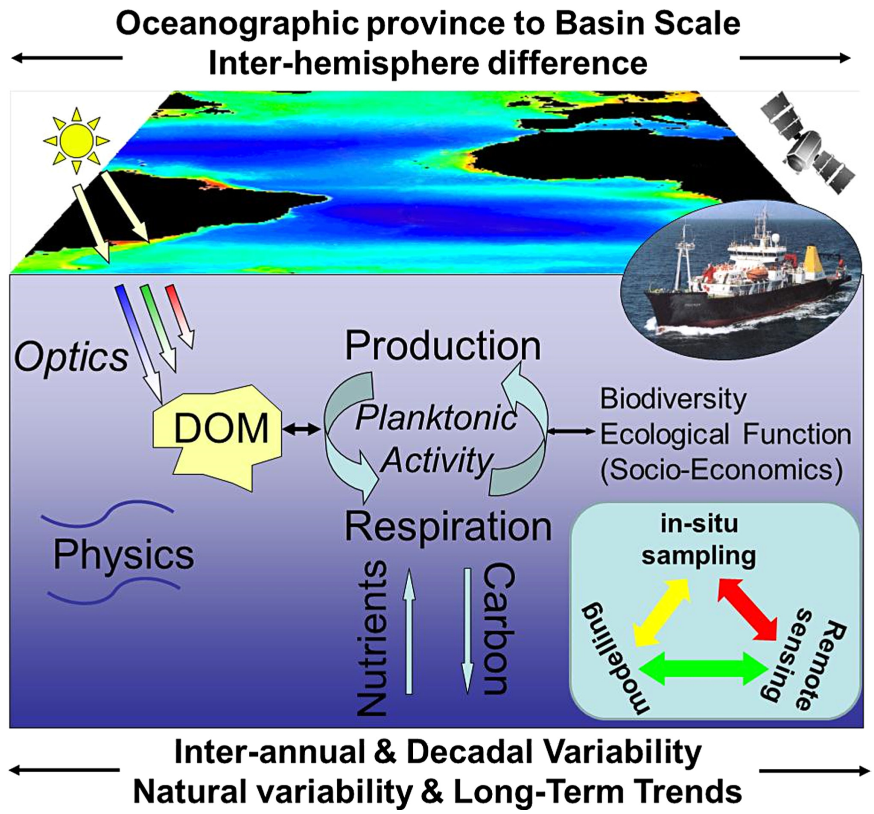

Fig. 4. Schematic representation of aims and objectives of AMT

3) Construction of multi-decadal, multidisciplinary ocean time-series which are integrated within a wider "Pole-to-Pole" observatory concept

AMT sails through some of the most remote parts of the Atlantic Ocean and supports sediment trap moorings in the central gyres of both hemispheres (http://noc.ac.uk/observatories/sog). This, therefore, makes it an ideal platform for the deployment of ARGO (collaboration with the UK Met Office) and Bio-Argo (LOV, France including EUROARGO). Based on expertise gained on AMTs with Bio-Argo, PML has purchased 11 Bio-Argo floats, this represents about 20% of the current number of such floats in operation globally. Bio-Argo promises to revolutionise the way that we observe the biogeochemistry of the upper 2000 m of the ocean, much in the same way that Argo has transformed our observational capability of the physics.

Measurements made during AMT transects are relevant to GOOS-IOCCP EOVs and also cover many of the UK Integrated Marine Observing Network initiative (UK-IMON) recognised core variables selected to monitor ecosystem structure and function (temperature, salinity, optical properties, ocean color, meteorology, dissolved oxygen, pH, dissolved nutrients, pCO_2, phytoplankton, zooplankton).

4) Sea-truth validation for current and next generation satellite missions

AMT provides a globally unique opportunity to validate across a wide range of ocean provinces, (critically the sparsely sampled oligotrophic gyres) visible ocean color sensors. This began in the late 1990's with the prelaunch and postlaunch SeaWiFS cruises, where critical measurements of in-water radiometry and in-situ measurements of HPLC chlorophyll were simultaneously sampled by PML and NASA scientists. With the launch of new sensors (ESA Sentinel series, NASA VIIRS) this need is arguably more pressing. During AMT-23 along track visible wavelength radiometers continuously monitored the hyperspectral (1.5 nm wavelength bands between 350 nm and 950 nm) water leaving radiance, a fundamental satellite measurand. Additionally, surface HPLC chlorophyll samples were taken for satellite algorithm validation. AMT-23 was also notable for the installation of a flow through system, attached to the non-toxic supply, continuously measuring the hyperspectral inherent optical properties (IOPs, absorption and backscatter). This will be used for the development of new satellite algorithms relevant for assimilation into global biogeochemical models. The collaboration with NASA AERONET continued, with measurements being taken of aerosol optical thickness along track using a hand held Microtops instrument. These data are essential for understanding the Earth's radiation budget, and are unique as they are sampled in some of the most inaccessible parts of the global ocean.

See http://aeronet.gsfc.nasa.gov/new_web/cruises_new/James_Clark_Ross_13.html

Collaborative exercises continue between PML and Oregon State University. In 2012 this supported a NASA aircraft field campaign which took simultaneous LIDAR measurements with in-situ data on AMT-22. This has resulted in novel findings relating to the carbon content of phytoplankton cells (Behrenfeld et al. 2013). One of the goals of ocean color remote sensing is to move beyond the determination of chlorophyll from satellite. The size spectra of phytoplankton is a critical metric in determining the flow of carbon and energy through the different trophic levels and this has been the subject of intense research activity in the past 5 years (Brotas et al. 2013).

5) Provide data for global ecosystem model development and validation

Under the EU funded programme "Greenseas", AMT data have been used to develop a new method to dynamically (temporal and spatial dimensions) determine the extent of oceanic provinces. This is done using an automatically generated classifier which is based on the seasonal patterns of bloom dynamics (*ICES report CM*. R:22 - R:22). The combined inputs of AMT observations with remotely sensed and modelled data have been used in the development of methods in the interrogation of long-term datasets in order to differentiate trends on scales of time (*ICES report CM*. R:11 - R:11). Dutkiewicz et al. (2015) have constructed a model with which to test the optical characteristics of ocean water. By comparing the model with concurrently measured biogeochemical, ecosystem, and optical data from AMT, there is good confidence that this new model captures bio-optical feedbacks and will be important for improving our understanding of the role of light and optical constituents on ocean biogeochemistry, especially in a changing environment.

6) Serve as unique training arena for the next generation of UK and International oceanographers

AMT continued its collaboration with POGO and provided a sponsored berth to fellows from developing countries to work under the mentor-ship of UK AMT funded scientists until 2014. For AMT-24 there were 30 applicants from 15 countries. During the last two cruises, Miss Ankita Misra from the Goa Institute of Oceanography, India worked with Gavin Tilstone on AMT23 to investigate primary productivity of surface waters and on AMT24 Mr Rafael Rasse from Instituto Venezolano de Investigaciones Cientificas, Venezuela worked with Giorgio Dall'Olmo on the relationship between particulate organic carbon and optical properties of seawater. AMT has contributed data and training experience for over 70 graduate students since 1995, a further six PhDs were successfully defended during the last 12 months.

Looking Forward

Financial, organisational and environmental change all offer challenges to the continuation and further development of a programme such as the AMT. Over the last twelve months a "Task Team" of interested parties from a cross section of disciplines and UK institutes and universities have provided guidance and aspiration to the aims of AMT into the future. The work of this team was strengthened and consolidated during plenary sessions of the AMT science conference and a forward looking document was produced with which to shape the future direction of AMT research. Future developments of the programme will be undertaken in an evolutionary way building on the evident successes of the current work and responding to new scientific questions and national and international priorities as they emerge.

As the backbone of a pole-to-pole in situ observing system, linking the north and south Atlantic, AMT will continue to extend the unique, multi-decadal biogeochemical time-series with a focus on validating and improving Earth System Models. As such this will advance our understanding of the Earth System as a whole, and the role that the oceans play within it, to enable us to quantify the nature and scale of global environmental change and associated implications for mitigation and adaption. AMT will play a crucial role in the calibration and validation of the next generation of Europe's environmental satellite platforms and will ensure a managed alliance of ship based and autonomous (vehicle) based observation.

Co-operation and collaboration have dictated the ethos of the AMT since its inception. This will continue and anybody interested in participating in AMT cruises is encouraged to contact Andy Rees at Plymouth Marine Laboratory (apre@pml.ac.uk). For access to the AMT database please contact Rob Thomas at the British Oceanographic Data Centre (room@bodc.ac.uk).

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Andrew Rees, Plymouth Marine Laboratory, Prospect Place, The Hoe, Plymouth, PL1 3DH, UK; apre@pml.ac.uk

Carol Robinson, University of East Anglia, School of Environmental Sciences, Norwich NR4 7TJ, UK; Carol.Robinson@uea.ac.uk

Tim Smyth, Plymouth Marine Laboratory, Prospect Place, The Hoe, Plymouth, PL1 3DH, UK; tjsm@pml.ac.uk

Jim Aiken, Plymouth Marine Laboratory, Prospect Place, The Hoe, Plymouth, PL1 3DH, UK; jimaiken@talktalk.net

Phil Nightingale, Plymouth Marine Laboratory, Prospect Place, The Hoe, Plymouth, PL1 3DH, UK; pdn@pml.ac.uk

Mike Zubkov, National Oceanography Center, Waterfront Campus, European Way, Southampton, Hampshire SO14 3ZH, UK; mvz@noc.ac.uk